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Rockfall Hazard Assessment in Volcanic Regions Based on ISVS and IRVS Geomechanical Indices

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Abstract: In volcanic regions, rockfalls represent a major hazard strongly conditioned by the geomechanical behaviour of volcanic materials, the geomorphological characteristics of the relief and the climatic conditions. Volcanic rocks possess very different properties to those of other lithological groups, presenting highly heterogeneous geomechanical behaviours. Nevertheless, they have received little research attention in the field of geological and geotechnical engineering. To date, the application of geomechanical classifications to characterise and estimate volcanic slope stability has not yielded reliable results, indicating the need to establish specific criteria for these rocks. Consequently, we developed indices to estimate rockfall susceptibility, hazard and risk in volcanic slopes. The index of susceptibility for volcanic slopes (ISVS) is designed to estimate slope susceptibility to instability, which is related to the level of hazard, while the index of risk for volcanic slopes (IRVS) is designed to estimate the level of risk as a function of the potential damage or economic loss caused as a result of rockfalls on slopes. Both indices were developed in order to provide an easily applied procedure that facilitates the adoption of short-term preventive measures against rockfalls. The indices were applied in Tenerife (Canary Islands), which presents exceptional conditions for analysing slope stability in volcanic rocks because of its mountainous orography with very steep slopes and a wide variety of materials. These conditions have frequently precipitated slope instability, causing significant damage to housing, beaches, roads and other infrastructures. After applying these indices to a number of slopes representative of the island's wide variety of geological, geomorphological and climatic conditions, the results obtained were compared with the actual behaviour of the slopes, determined from extensive rockfall inventory data and *in situ* geomechanical surveys.

Keywords: rockfall hazard; slope stability; volcanic rocks; geomechanical classifications; volcanic islands

1. Introduction

The processes involved in slope instability and rockfall risk in volcanic regions have received little research attention, despite the high economic losses and significant social impacts these hazards entail, especially in relation to roads, housing, coastal areas and beaches. Instability processes have a significant social impact because they affect road and transport safety and people in urban and recreational areas, and often require short-term preventive measures. Consequently, there is a need for decision-making criteria and proposals for possible solutions [1–4].

Given the particular geological and geomechanical conditions of volcanic rocks, it is necessary to develop specific methods to estimate slope stability, the probability of rockfalls and the possible economic consequences. Here, we present a method for performing such estimations.

The main factors that determine slope stability in volcanic regions are the geomechanical properties of the rocks and the geomorphologic and climatic conditions of the slopes. As a lithological group, volcanic materials are very distinct from other geological materials because of their atypical geomechanical behaviour. The main properties determining this behaviour include: their high heterogeneity and anisotropy, due to their geostructural and fracture characteristics as well as their geomechanical properties; the existence of substantial differences between deposits; the predominance of discontinuities of thermal origin with very different fracture systems from non-volcanic materials; and the rapid degradation of strength properties by alteration processes, giving rise to secondary, geotechnically unfavourable minerals such as smectites [5,6].

One of the most important factors determining stability is slope geomorphology, which can be very steep, especially in oceanic volcanic islands. Meanwhile, the main factor that triggers rockfalls is rainfall, which exacerbates instability processes, especially in tropical climates [7,8].

In recent decades, the construction of large infrastructures in volcanic regions has aroused interest in advancing geotechnical knowledge of these materials, prompting numerous geotechnical studies aimed at excavation design and slope stabilisation, many of which were presented at the international workshops held on these rocks [9–12].

These studies have generally used RMR (Rock Mass Rating) [13] and Q-system [14] geomechanical classifications and the geological index GSI (Geological Strength Index) [15,16] to characterise rock masses and their properties. However, these classifications were developed based on rocks whose origin was not, for the most part, volcanic, calling into question the suitability of their application to volcanic rocks. Alternatively, several geomechanical classifications specific to these rocks have been proposed [17–19]. These classifications apply different criteria: the first two are based on the RMR, whereas the third proposes a new classification system.

Rockfalls in volcanic regions are often difficult to predict and frequently demand short or medium-term preventive measures with little time to perform geotechnical studies or risk analyses. It is therefore highly desirable to develop easily applied procedures to assess slope stability. To this end, we developed two geomechanical indices, one that is designed to identify slopes presenting the highest susceptibility to instability, based on observable in situ data, and the other to estimate the degree of rockfall risk and provide recommendations for the adoption of preventive measures.

The ISVS (index of susceptibility for volcanic slopes) is designed to estimate slope susceptibility (possibility of occurrence) to instability, which can be empirically related to the degree of hazard (probability of occurrence), while the IRVS (index of risk for volcanic slopes) provides a simplified means to estimate the degree of risk as a function of the potential damage or economic loss caused as a result of rockfalls.

The indices were applied in Tenerife (Canary Islands), which presents exceptional conditions for analysing slope stability in volcanic rocks because of its mountainous orography with very steep slopes and a wide variety of materials. These conditions have frequently precipitated slope instability, causing significant damage to housing, beaches, roads and other infrastructures.

2. Estimating Rockfall Susceptibility: The ISVS Index

In order to estimate the degree of instability in volcanic slopes, we developed a susceptibility index, the ISVS, based on geological, geomorphological and geomechanical data, with the following objectives: (i) to provide a wide range of professionals—not necessarily experts—with an easily applied, affordable procedure to conduct an initial stability assessment at short notice, prior to geotechnical and risk studies; (ii) to identify areas at greater risk of instability and (iii) to provide criteria for the adoption of short-term preventive measures where necessary.

The ISVS is based on the following parameters:

A. Type of rock mass, which includes the following lithological groups:

- Type I: rock masses formed by hard rock (>20 MPa) such as basalt, trachyte, phonolite, rhyolite and ignimbrite, together with highly compacted or welded tuffs and breccias. The factors influencing stability in this type of rock mass are the degree of fracturing and dip of the geological structure and the main discontinuity surfaces, where these are parallel to the slope direction. The most frequent instabilities are rockfalls caused by wedge failures, whether along planar surfaces or by toppling.
- Type II: deposits of pyroclastic origin that are poorly compacted, loose or weakly welded. The main factor influencing stability is the degree of compaction or welding of pyroclastic particles. The most frequent instabilities are falls of loose materials or large blocks such as volcanic bombs.
- Type III: rock masses formed by alternations or sequences of materials presenting different strengths. Weaker layers are more susceptible to erosive processes, undermining the base of harder layers and causing rocks or blocks to fall. For example, on slopes with basalt flows, scoria and pyroclastic layers, erosion of the latter causes blocks of the stronger materials to fall. The factors influencing instability are the degree of differential erosion between materials of different strengths and the formation of rock overhangs in hard layers. Figure 1 shows some examples of the types of rock mass described. Tables 1 and 2 give the parameters to consider and their scores.

B. Slope angle, classified into three intervals (<45°, 45–75° and >75°) according to the slope angle/instability relationship obtained from an extensive database [20,21]. Table 1 shows the scores assigned to the angle intervals.

C. Sea or gully erosion. Slope proximity to the coast or gullies constitutes a decisive factor for instability. We established a distance of up to 50 m from the sea at high tide, or a gully, as the reference value for applying this penalty factor (Table 1).

D. Instability indicators. The existence of fallen blocks, cracks, escarpments, etc., on a slope, and damage to nearby buildings or roads, are indicators of active instability processes and were included in the ISVS as a penalty factor. This factor is estimated according to the number of indicators observed, both on the ground and in nearby structures (Table 1).

The ISVS is calculated by applying and scoring the above criteria as indicated in Table 1, establishing four degrees of susceptibility to instability. The score ranges from 0 to 100 points, where 100 is the maximum value for susceptibility, although higher values can be obtained in the calculation. The ISVS is not applicable to highly weathered or altered rocks, colluvial deposits or soils. The flow diagram shown in Figure 2 illustrates the procedure for applying the ISVS.

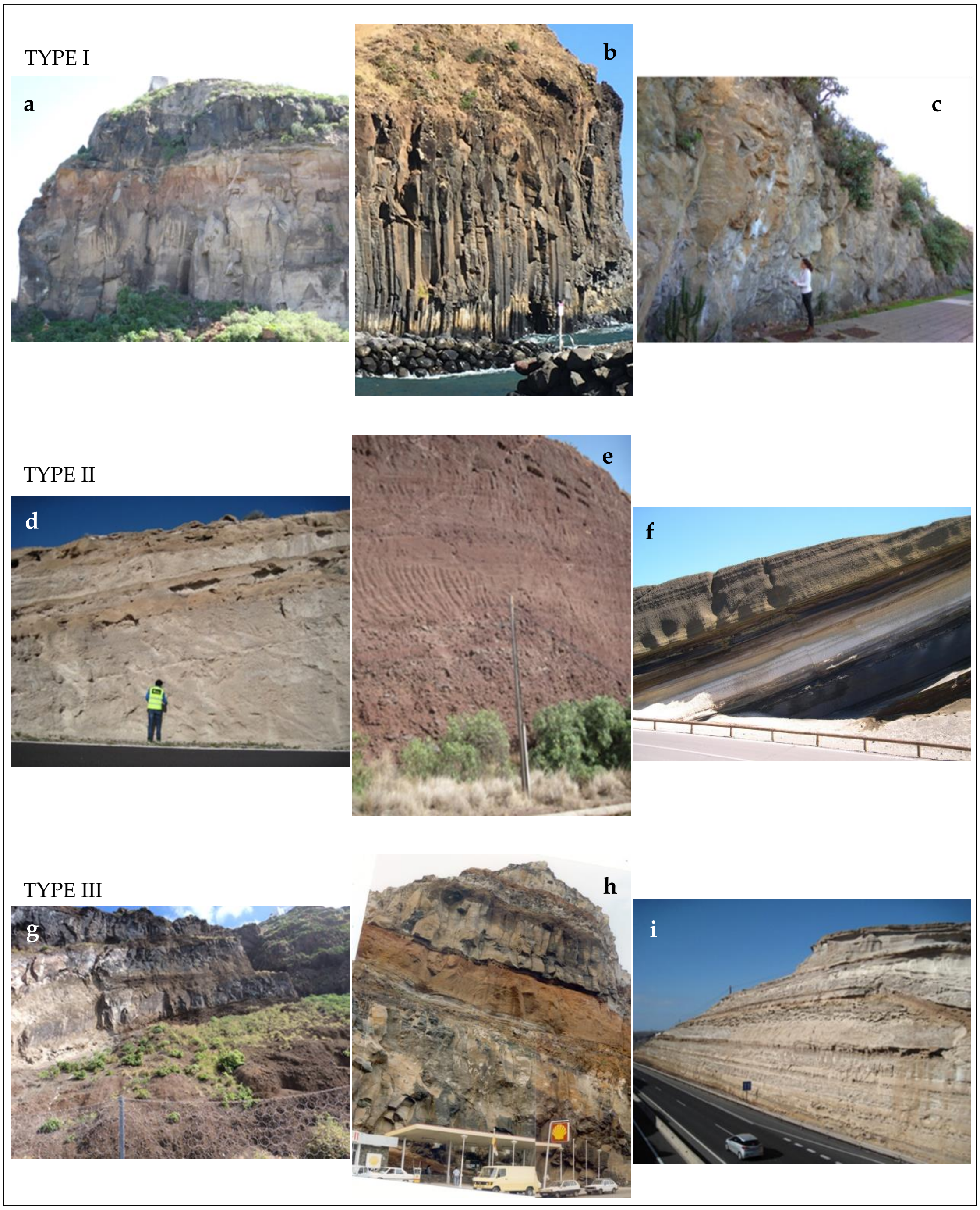


Figure 1. Examples of rock masses according to index of susceptibility for volcanic slopes (ISVS). Type I, hard rocks: (**a**) welded tuff, ignimbrite; (**b**) columnar basaltic lava flows; (**c**) trachytes. Type II, pyroclastic deposits: (**d**) unwelded ignimbrites; (**e**) massive basaltic tuffs; (**f**) salic and basaltic pyroclasts. Type III, alternation of layers with different strength: (**g**) basaltic lava flows and scoria layers; (**h**) basaltic flows alternating with pyroclastic levels and (**i**) unwelded ignimbrites alternating with salic fall pyroclasts.

Table 1. ISVS: parameters and scores.

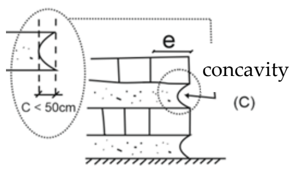
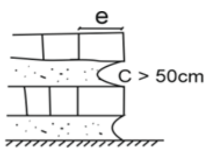
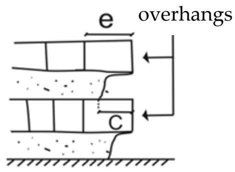
A. Rock Mass Type					
Type I: Hard Rocks		**Type II: Pyroclastic Deposits**		**Type III: Sequence of Layers with Different Strengths**	
1. Degree of fracture	Pt	1. Degree of compaction/ welding (*)	Pt	1. Degree of differential erosion (*)	Pt
Massive: <1 joint/m^3	0	High	0	Low	0
Low: 1–3 joints/m^3	5	Medium	5	Medium	15
Moderate: 3–10/m^3	20	Low	25	High	30
High: >10 joints/m^3	30	Very Low	35	2. Overhang formation (*)	
2. Dip of geological structure or main discontinuity surfaces dipping to slope face	Pt			Very small blocks	0
<20°	0			Small blocks	10
20–40°	5			Medium blocks	30
>40°	10			Large blocks	40

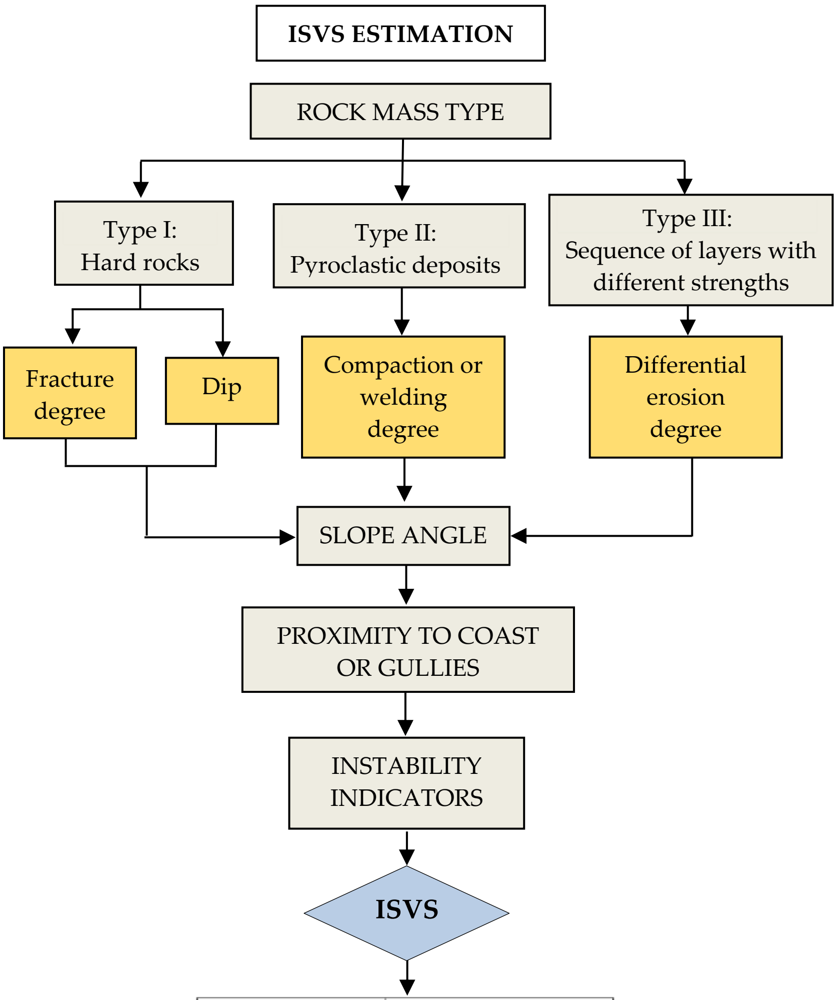
B. Slope Angle			**C. Proximity to Coast Or Gullies**		**D. Instability Indicators**	
Average slope angle		Pt	Slopes <50 m	Pt	Number of indicators	F
<45°	Moderate	0	from high tides or gullies	10	0	1
45–75°	High	10			1 to 3	1.2
>75°	Very High	20			>3	1.35

Instability Indicators	**ISVS Estimation**	
Scarps and cracks		
Ground bulges and deformations	ISVS $_{basic}$ = [AI(1+2) or AII(1) or AIII(1+2)] + B + C	
Fallen blocks or recent signs of failure surfaces		
Diversion of channels		
Accumulation of deposits at the foot of slopes	ISVS = ISVS $_{basic}$ · D	
Ponding	**ISVS**	
Water surges and changes in water sources	Score	SUSCEPTIBILITY
Tree tilting	<35	Low
Cracks in walls, foundations or other structural elements	35–59	Moderate
Tilt and collapse of walls	60–79	High
Broken pipes	≥80	Very High

NOTES: (*) See Table 2 Maximum ISVS score: 100. Not applicable to soils, colluvial deposits or highly weathered rocks. Susceptibility indicates possibility of occurrence. Only one of the options for type of rock mass can be selected: I, II or III. For type III rock mass without differential erosion, types I or II will be selected. Only one option is selected for each parameter in the score assignment.

Table 2. Parameters applicable to Type II and III rock masses.

Parameter	Degree	Description		ISVS Rating
II.1. Degree of compaction/welding	Medium	Difficult to break with geological hammer		5
	Low	Easily broken with geological hammer		25
	Very low	Easily broken with hand		35
III.1. Differential erosion	Low	C < 15 cm		0
	Medium	Small concavities in the weathered materials C < 50 cm		15
	High	Large concavities C ≥ 50 cm		30
III.2. Overhang formation	Small blocks C < 25 cm and e/C < 2			10
	Medium blocks 25 ≤ C < 50 cm and e/C < 2			30
	Large blocks C ≥ 50 cm and e/C < 2			40



ISVS Score	Susceptibility
<35	Low
35–59	Moderate
60–79	High
≥80	Very High

Figure 2. Flowchart for estimating the ISVS (see Table 1).

3. Estimating Rockfall Hazard

Hazard refers to the probability (P) that an event of a given intensity or magnitude will occur in a given spatial area within a given period of time [22,23]. This can be estimated from the return period (T) of the event concerned (P = 1/T) and is expressed as the annual probability of exceedance (P_y) or the probability of occurrence during the service life of a given exposed structure or element (P_n). The return period can be estimated from observation of the number and size of rockfalls over a given period of time.

To estimate rockfall frequency in a volcanic zone, we used records of rockfalls affecting the road network in Tenerife, with more than 2000 events in the last 25 years [24,25]. In addition, we compiled other data on rockfalls in urban areas, coasts and beaches, gullies, etc., from publications, technical reports, newspaper archives and city councils, with events that date back more than 100 years.

We also conducted an in situ survey of slopes adjoining Tenerife's road network, selecting those most representative of different geological and geometric conditions from the point of view of stability, noting the number of fallen blocks, and calculating the ISVS for each of them. On the basis of the data collected from 95 representative slopes from Tenerife (see Section 5) and the information obtained by [24,25], we established characteristic intervals for rockfall frequency, return periods and ISVS values (Table 3).

Table 3. ISVS and rockfall frequency.

ISVS		Rockfall Frequency		
Score	**Susceptibility**	**Field Observations (1)**	**Rockfall Event History (2)**	**T (Years) (3)**
<35	Low	No fallen blocks	No record of rockfall in the area	≥100
35–59	Moderate	Some fallen blocks of small or medium size	No record of rockfall in the area	≥50
60–79	High	Several fallen blocks of different sizes	Some record of rockfalls in the last 50 years	≥25
≥80	Very High	Numerous fallen blocks of different sizes	Several records of rockfalls in the last 25 years	<25

(1) In situ observation of fallen blocks, signs of instability and rock failures in source areas. Small rocks or fragments of rock are excluded. (2) Based on data collected from field surveys, road maintenance records, technical reports, town halls, witnesses, newspaper libraries and the literature. (3) T = return period.

Hazard also depends on the action of factors that trigger rockfalls, such as rainfall, earthquakes and anthropic actions, where rainfall is the most frequent and important factor, and the only triggering factor here considered. Thus, hazard (HA) is expressed as HA = $P_y \cdot$ PF, or alternatively, as HA = P_n $\cdot$ PF, where P_y and P_n are the abovementioned probabilities and PF is the precipitation factor. This latter factor indicates the rainfall intensity threshold beyond which a significant increase in rockfalls will occur in an area. The relationship between rainfall and rockfalls varies across regions, since other factors are involved, including climatic and geomorphological conditions and the geomechanical properties of rock masses.

In order to estimate PF values in a volcanic region according to the rainfall-rockfall relationship, we analysed databases for rockfalls affecting roads in Tenerife [24,25] and the rainfall recorded during the events [26]. The results are given in Figure 3, while Figure 4 shows the relationship between rockfall probability and rainfall intensity [27]. Lastly, based on these data we estimated the precipitation factor (PF) and hazard (HA) (Table 4).

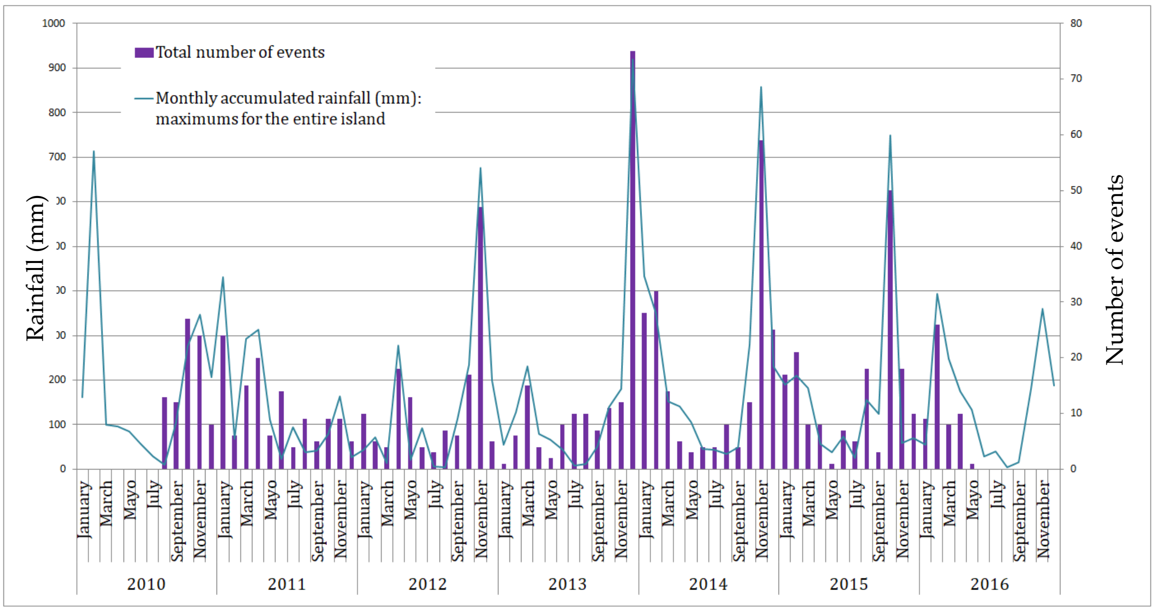


Figure 3. Relationship between rainfall and number of rockfall events from data recorded in Tenerife [26].

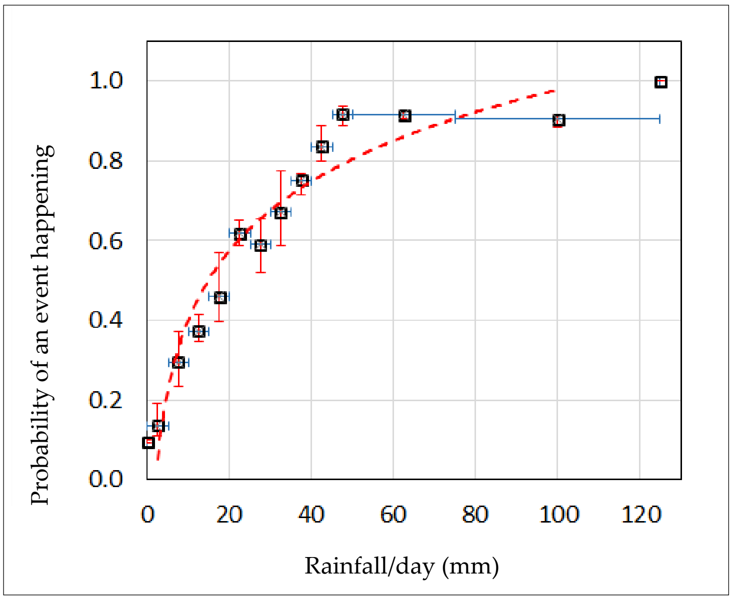


Figure 4. Probability of rockfalls according to rainfall intensity in Tenerife [27].

Table 4. Hazard estimation.

Probability (P)					Precipitation Factor (PF)		Hazard (HA)	
Susceptibility ISVS	**Return Period T (Years)**	**P_y (1)**	**P_n (2)**		**Precipitation (mm/Day)**	**PF (3)**	**HA = $P_n \cdot$ PF**	**Degree**
<35 Low	≥100	<0.01	<0.5	Low Moderate	<30	1	<0.25	Low
35–59 Moderate	≥50	≥0.01 <0.02	≥0.5 <0.75	High	<50	1.7	≥0.25 <0.5	Mode rate
60–79 High	≥25	≥0.02 <0.04	≥0.7 <0.94	Very High	≥50	2	≥0.5 <0.75	High
≥80 Very High	<25	≥0.04	≥0.94	Very High			≥ 0.75	Very High

(1) P_y = Annual probability of exceedance. (2) Probability of occurrence in *n* years: $P_n = 1-(1-1/T)^n$; n is the service life of a house or installation; 70 years have been taken as a reference. (3) Data for Tenerife.

4. Estimating Rockfall Risk: The IRVS Index

The index of rockfall risk for volcanic slopes (IRVS) was developed with the same general objectives as those for the ISVS: (i) to provide a means to estimate the degree of risk at short notice; (ii) to facilitate decision-making in situations requiring the adoption of short-term preventive measures and (iii) to conduct zoning according to the relative level of risk. Its scope is limited to a preliminary assessment prior to quantitative risk analyses procedures (QRA) [28,29].

The IRVS is expressed as a function of the hazard or probability of occurrence of a rockfall and the possible damage or losses caused to elements potentially exposed to risk [22,23,30]. The IRVS is calculated according to the expression IRVS = HA · LI, where HA is the hazard, and LI is the loss index. HA is obtained as described above, and the LI is calculated using the following expression LI = V · EC · CC, where V is vulnerability, EC is the energy increment coefficient for impact energy due to the height of the fall, and CC is the cost coefficient for damage or loss. Figure 5 summarises the procedure for applying the IRVS. Social and environmental costs are not included in this index.

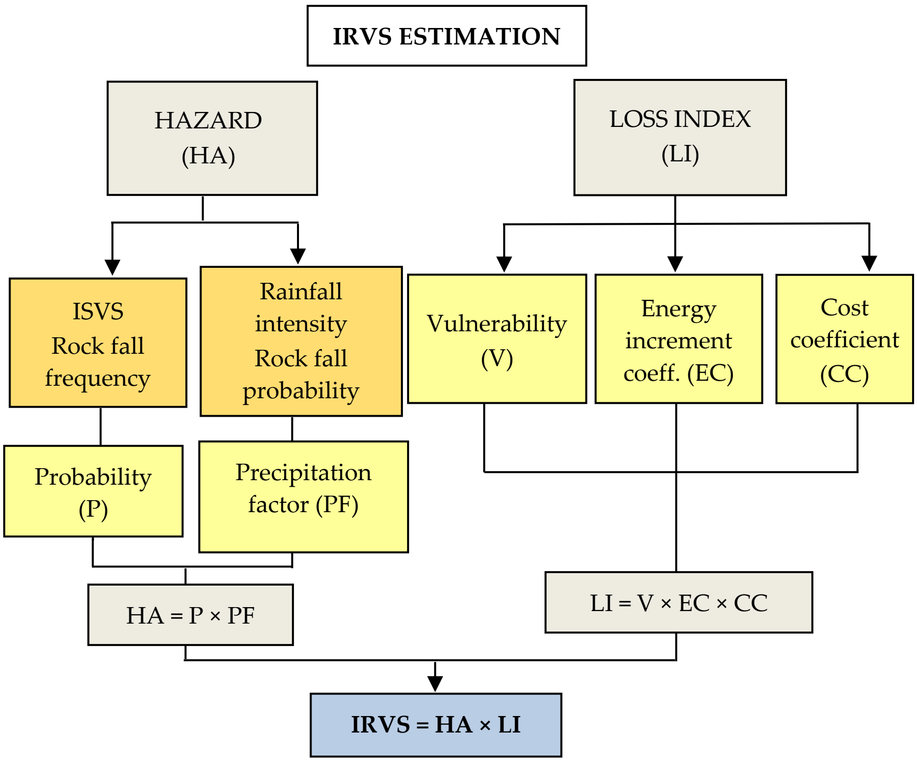


Figure 5. Flowchart for estimating the IRVS (see Tables 4 and 5).

Table 5. Loss index estimation.

Vulnerability (V)		**Energy Increment Coefficient (EC *)**			**Cost Coefficient (CC)**		**Loss Index (LI) LI = V·EC·CC**	
Type of Element	**Frequent Vulnerability Values**	**Slope Height (m) (*)**	**Impact Energy**	**EC**	**Cost (€ × 10^3)**	**CC**	**LI**	**Degree of Loss**
Households	0.2–0.8	≤10	Low	1	<50	1	≤2	Low
Urban centres	0.1–0.2	≤20	Moderate	1.5	<200	3	≤4	Moderate
Industrial facilities	0.1–0.2	≤30	High	2.5	<1000	8	≤8	High
Recreational areas	0.1–0.3	>30	Very High	3.5	≥1000	15–20	>8	Very High

(*) The block is considered to fall from the highest part of the slope, with a weight of 1 t; slope angle of 70°.

The parameters considered to calculate V, EC and CC are shown in Table 5, according to the following criteria:

- The vulnerability of exposed elements (V) that may be affected by the rockfall and the degree of loss that such elements may experience due to a hazard of a given intensity. Vulnerability varies depending on the characteristics of an element and the magnitude or intensity of the event, and is expressed according to the percentage that may be affected, either in percent or on a scale of 0–1.
- The energy increment coefficient (EC) is related to the height from which a block on a slope falls. This was estimated by simulating rockfalls at different heights and slope angles, for blocks weighing 0.5, 1 and 2 t, and slope heights measuring between 10 and 90 m (Figure 6). Rockfall simulations were carried out using Rockfall 6.011.2008 program from Rockscience Inc. Coefficients of restitution Rn = 0.53 and Rt = 0.95 were applied according to the experience on basaltic rock masses from the Canary Islands [26].
- The cost coefficient (CC) refers to the economic losses of an exposed element affected by rockfalls.

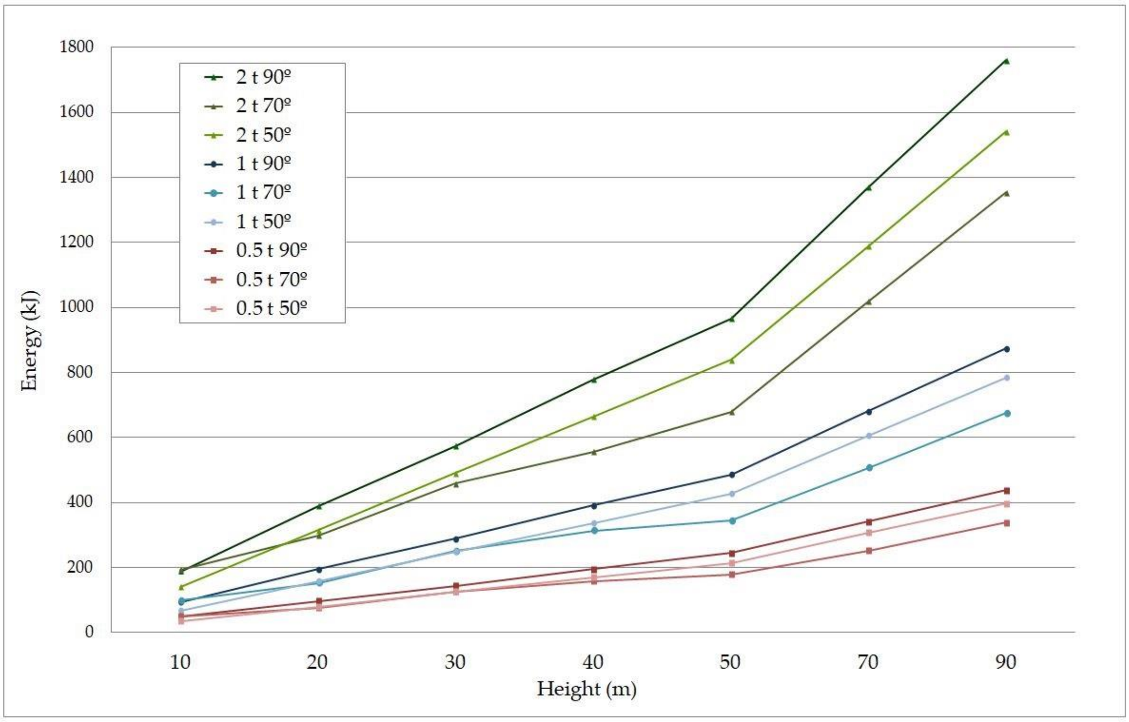


Figure 6. Kinetic energy of rockfall impact for blocks with different weights, fall heights and slope angles.

Hazard (HA) and the loss index (LI; Tables 4 and 5 respectively) were used to estimate the IRVS (IRVS = HA · LI) and degree of risk (Table 6). Table 6 gives some recommendations for preventive measures.

Table 6. Degree of risk estimated from IRVS and recommendations.

IRVS	Risk Level	Preventive Measures	Priority of Action
<1	Low	None	Not required
1–3	Moderate	Site evaluation	In the medium term
3–6	High	Detailed survey	Short to very short term
>6	Very High		

The different degrees of risk considered might vary according to subjective criteria such as social perception of risk, an aspect that is not considered in the IRVS but which would be of interest in a possible situation of social risk [22,31]. To analyse the potential impact of this aspect, we conducted a survey among university graduates unfamiliar with the geosciences, asking them how they would classify the level of risk of a rockfall that could affect a house according to the different levels of hazard and losses obtained from the IRVS. The results obtained (Figure 7) show some differences with respect to the degrees of risk considered in the IRVS (Table 6): respondents proposed three degrees of risk instead of four, due to difficulties in differentiating between the high and very high degrees; we also noted a tendency to overestimate the degree of risk with respect to that estimated using the IRVS. These results may be useful in possible situations of personal injury or social consequences.

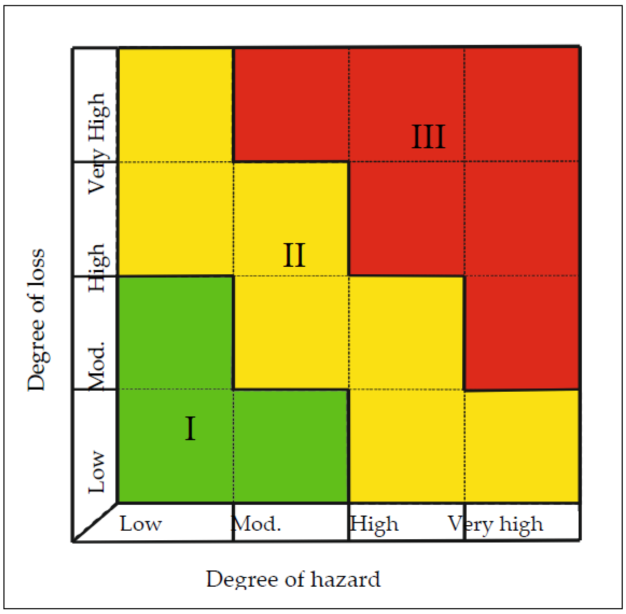


Figure 7. Estimated degree of risk according to social perception of risk. I: Low; II: Moderate; III: High–Very High.

5. Application of the ISVS in Tenerife and Discussion of the Results

The ISVS was applied in Tenerife (Canary Islands) because it offers ideal conditions for analysing rockfalls in volcanic slopes (Figure 8). Based on the information available on previous rockfalls affecting roads [24,25], urban areas, coasts and beaches, we identified a number of areas of interest for applying the ISVS. These areas were geologically and geomechanically characterised, selecting 95 slopes representative of the different types of rock mass and geomorphological and climatic zones in Tenerife [32]. The location of the slopes and their corresponding rock mass type are given in Figure 9. Appendix A gives detailed data on the slopes analysed.

We estimated the ISVS value for the selected slopes according to their history of rockfalls (ISVS $_{\text{assigned}}$), and then compared this value with the one calculated *in situ* (ISVS $_{in\ situ}$). Figure 10 shows the relationship between the two, which obtained a correlation coefficient of 0.97. These results reflect the successive adjustments made to the scores during development of the ISVS, until the results obtained agreed with the actual behaviour of the slope, thus verifying the validity of the parameters considered in the ISVS.

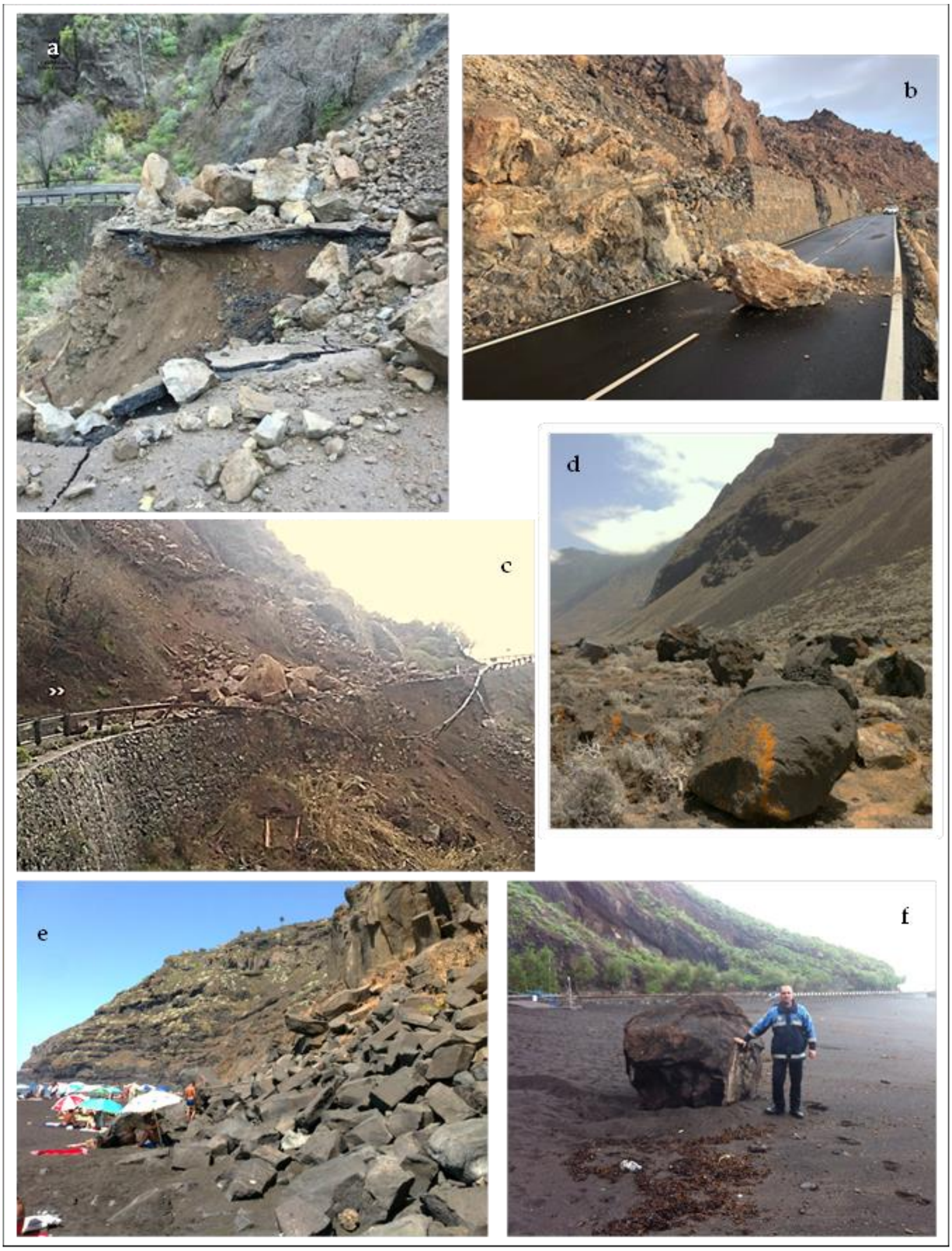


Figure 8. Examples of rockfalls on volcanic slopes in the Canary Islands. (**a**) Rock avalanche in salic materials; (**b**) rockfall in phonolitic lava flows; (**c**) rock avalanche in weathered materials; (**d**) volcanic bombs fall from pyroclastic deposits; (**e**) rockfalls by columnar basalts toppling on a beach and (**f**) large basaltic block fallen on a beach.

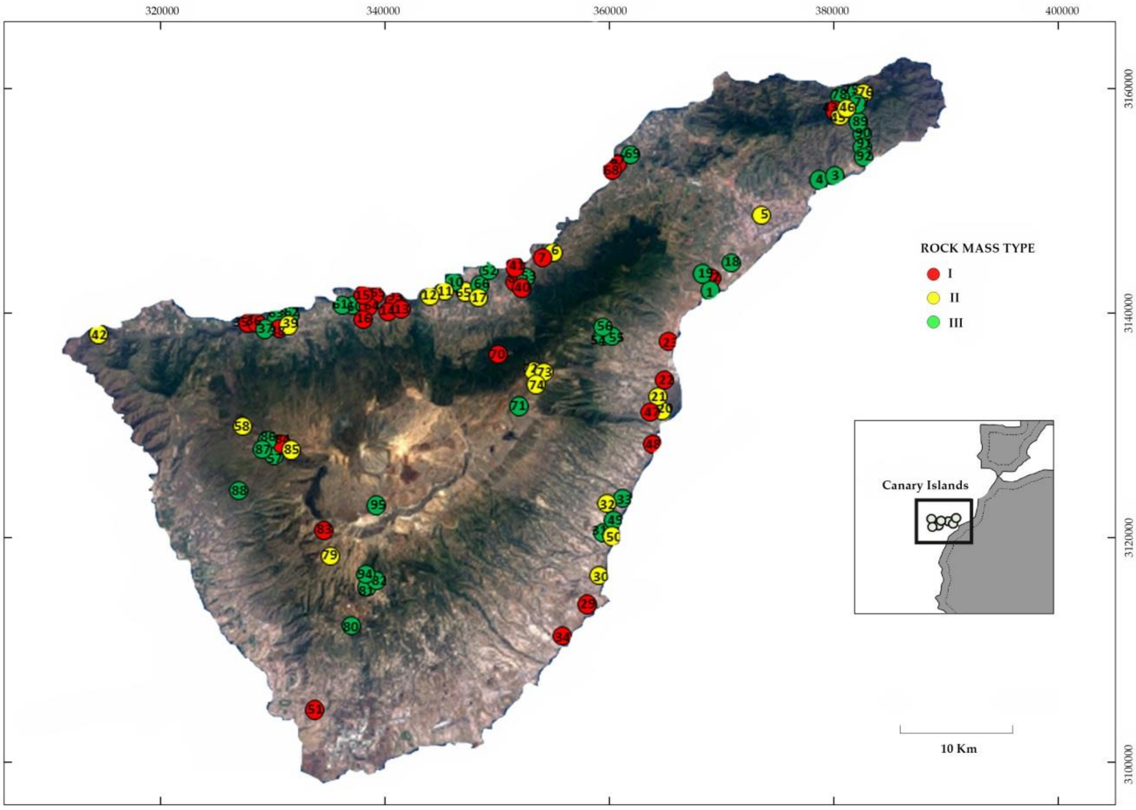


Figure 9. Location of the slopes analysed in Tenerife according to the type of rock mass.

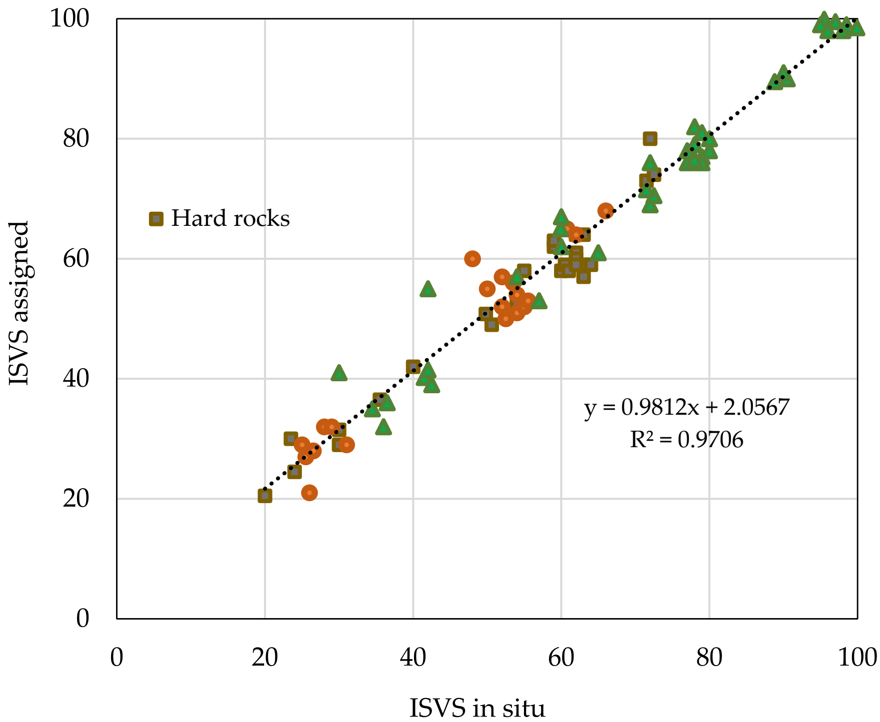


Figure 10. Relationship between the ISVS estimated in situ and the ISVS assigned according to the actual slope behaviour.

Recently, studies have been conducted in Tenerife to analyse application of the abovementioned geomechanical classifications to slope stability in volcanic rocks [33]. The results obtained from an analysis of 42 slopes show that the classification described by [18] cannot be used to assess the degree of slope stability, although it may be suitable to estimate the geomechanical quality of the rock mass. Meanwhile, the classification proposed by [19] evidences significative differences with respect to the actual behaviour of the slopes, with a tendency to overestimate slope stability. When the ISVS was applied, a correlation coefficient of 0.95 was obtained between the index values and those estimated according to actual slope behaviour.

The ISVS can be applied to other volcanic regions since its parameters do not depend on local factors. In this respect, further studies are being conducted in Mexico, which have obtained positive results to date [34]. However, it is evident that more data is required on other volcanic areas and regions. When applying the IRVS, the precipitation factor must be adjusted to the climatic conditions of each region.

6. Conclusions

In response to the need for specific criteria to analyse slope stability in volcanic rocks, we developed a rockfall susceptibility index, the ISVS, and a rockfall risk index, the IRSV. Both indices were developed in order to provide an easily applied procedure that facilitates the adoption of short-term preventive measures against rockfalls.

The ISVS is based on four parameters that exert a considerable influence on stability: type of rock mass, slope angle, incidence of erosive processes and presence of instability indicators. The IRVS is based on currently used methods for estimating hazard and risk, and on the use of empirical relationships to estimate the probability of rockfalls and the influence of rainfall on such events.

The ISVS was applied in Tenerife, analysing 95 slopes representative of the island's geological, geomorphological and climatic conditions. The information available on rockfalls affecting roads, urban areas, coasts and beaches was used to obtain the history of rockfalls on the slopes analysed. These data were used as a reference to analyse the validity of the ISVS. The relationship obtained between the ISVS estimated in situ, in accordance with the developed procedure, and the ISVS assigned in accordance with historical rockfalls on the slope, showed a high degree of correlation.

The ISVS can be applied to any volcanic region, within the previously established limitations. However, when applying the IRVS, the precipitation factor must be adjusted to the climatic conditions specific to each region, although the values suggested in the present study may provide tentative guidance should other data be unavailable. The information provided by the ISVS and IRVS will help ensure the safety of infrastructures and people by enabling identification of those slopes with a higher risk of rockfalls and adoption of the necessary preventive measures.

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Appendix A

Table A1. Slopes investigated in Tenerife

N° Slope	Coordinates (N/W)		Type of Rock Mass (*)	ISVS (**)		
				In Situ	Assigned	Susceptibility
1	2.840.269.444	−163.391.389	III	42	40	Moderate
2	2.840.269.444	−163.391.389	I	30	30	Low
3	2.849.227.778	−162.198.889	III	72	70	High
4	2.848.719.444	−162.349.167	III	60	65	High
5	2.845.958.333	−162.908.889	II	30	31	Low
6	2.842.444.444	−164.797.222	II	30	30	Low
7	28.43	−16.49	I	50	50	Moderate
8	284.035	−165.136.944	I	35	30	Low
10	2.840.083.333	−165.686.111	III	60	62	High
11	283.975	−165.788.889	II	25	25	Low
12	2.839.472.222	−165.933.333	II	54	54	Moderate
13	2.839.277.778	−166.155.556	I	60	63	High
14	2.839.166.667	−166.252.778	I	24	25	Low
15	2.839.555.556	−166.413.889	I	60	66	High
16	2.839.333.333	−166.530.556	I	62	62	High
17	2.839.888.889	−165.441.667	II	48	60	High
18	2.842.055.556	−163.161.111	III	72	71	High
19	2.840.638.889	−163.322.222	III	42	41	Moderate
20	2.830.083.333	−163.777.778	II	54	54	Moderate
21	2.830.944.444	−163.822.222	II	60	67	High
22	28.33	−163.730.556	I	60	61	High
23	283.575	−163.725	I	60	58	Moderate
24	2.865.833.333	−178.736.111	III	42	55	Moderate
25	2.857.083.333	−178.730.556	III	30	41	Moderate
26	2.854.138.889	−178.669.444	III	60	61	High
27	2.853.083.333	−178.636.111	III	60	71	High
28	2.849.916.667	−178.538.889	II	61	70	High
29	2.814.694.444	−164.527.778	I	30	31	Low
31	2.820.055.556	−164.263.889	III	42	42	Moderate
32	2.822.527.778	−164.294.444	II	30	32	Low
34	2.811.555.556	−164.730.556	I	36	35	Low
35	2.837.138.889	−167.533.333	I	60	64	High
36	2.837.138.889	−167.533.333	I	72	72	High
37	28.37	−167.319.444	III	35	36	Moderate
38	2.837.295.833	−167.329.361	I	60	60	High
39	2.837.295.833	−167.329.361	II	25	26	Low
40	284.035	−165.136.944	I	24	24	Low
41	2.841.805.556	−165.136.944	I	40	42	Moderate
43	2.854.016.944	−162.281.722	I	50	51	Moderate
45	2.853.901.667	-162.192.278	II	30	32	Low
46	28.547.125	−162.124.139	II	25	26	Low
47	2.829.935	−163.848.222	I	60	64	High
48	2.827.305.556	−163.849.306	I	54	54	Moderate
49	2.821.230.278	−164.233.528	III	36	35	Low
50	2.819.723.056	-164.263.194	II	25	27	Low
51	2.805.953.056	−166.905.194	I	20	20	Low
52	2.841.638.889	−165.399	III	100	100	Very High

Table A1. *Cont.*

N° Slope	Coordinates (N/W)		Type of Rock Mass (*)	ISVS (**)		
				In Situ	Assigned	Susceptibility
53	28.403.525	−165.063.639	III	85	80	Very High
54	28.359.596	−16.427.687	III	100	78	High
55	28.359.596	−16.427.687	III	100	78	High
56	2.836.523.333	−164.317.694	III	78	78	High
57	28.262.699	−16.721.826	III	78	78	High
58	28.282.291	−16.759.929	II	54	54	Moderate
59	28.395.447	−16.641.457	I	60	60	High
60	28.384.465	−16.661.344	III	96	96	Very High
61	28.384.465	−16.661.344	III	96	96	Very High
62	2.837.784	−16.721.676	III	90	72	High
63	2.837.636	−16.728.338	III	100	100	Very High
64	2.839.211	−16.652.258	I	42	60	High
65	28.392.749	−16.560.064	II	54	66	High
66	28.403.227	−16.538.762	III	100	100	Very High
67	28.501.822	−16.424.532	I	60	60	High
68	28.501.822	−16.424.532	I	60	60	High
69	28.501.164	−16.422.387	III	54	54	Moderate
70	28.340.758	−16.525.257	I	60	60	High
71	28.304.984	−16.507.708	III	96	96	Very High
72	28.334.471	−16.489.994	II	54	54	Moderate
73	28.334.471	−16.489.994	II	54	54	Moderate
74	28.334.932	−16.491.067	II	54	54	Moderate
75	28.558.409	−16.205.669	III	36	36	Moderate
76	28.558.409	−16.205.669	II	54	54	Moderate
77	28.553.838	−16.208.707	III	78	78	High
78	28.559.011	−16.216.629	III	100	100	Very High
79	28.177.603	−16.673.352	II	54	54	Moderate
80	28.125.951	−16.660.136	III	78	78	High
81	28.159.374	−16.638.348	III	78	78	High
82	28.164.092	−16.638.387	III	42	100	Very High
83	28.208.221	−16.679.319	I	60	60	High
84	28.274.098	−16.728.251	I	72	72	High
85	28.274.095	−16.728.251	II	66	54	Moderate
86	28.266.742	−16.736.684	III	72	72	High
87	28.263.197	−16.737.592	III	100	78	High
88	28.231.522	−16.760.112	III	100	78	High
89	28.535	−16.198.333	III	90	78	High
90	28.526.389	−16.195.278	III	78	36	Moderate
91	28.517.444	−16.193.722	III	54	54	Moderate
92	28.511.389	−161.925	III	90	90	Very High
93	2.839.152.778	−166.252.472	I	42	42	Moderate
94	28.165.375	−166.365.306	III	90	90	Very High
95	28.224.167	−16.631.111	III	100	100	Very High

(*)Type I: Hard rock. Type II: Pyroclastic deposits. Type III: Sequence of layers with different strength. (**) ISVS assigned is referred to actual behaviour of the slope stability (see Section 5).

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